Determination of design shear strength of clay based on the comparison between unconfined compressive strength and the strength obtained by triaxial test

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ABSTRACT

To determine the design shear strength of seabed, the method by unconfined compressive strength with the combined use of triaxial CU test (combined method) had been proposed. The combined method was used in 4th runway project of Tokyo International Airport and in the construction project of breakwater in Sakai-Minato Port. In the 4th runway project, it was found that the quality of high plastic clay taken by fixed piston thin wall sampler or Denison type triple tube sampler was fairly good and that the combined method was effective to avoid the underestimation of strength of low plastic clay. In the case of Sakai-Minato Port, although the breakwater had been constructed on improved ground previously, the breakwater could be constructed without any improvement, because the strength of intermediate soil was evaluated correctly by the combined method.

Keywords: clay, shear strength, triaxial test, unconfined compression test, intermediate soil

1. INTRODUCTION

The design shear strength $s_{u(UCT)}$ of clayey ground has been determined by unconfined compressive strength q_u of undisturbed clay samples with the following equation¹⁾.

$$s_{u(UCT)} = q_{u(ave.)/2} \quad (1)$$

where $q_{u(ave.)}$ is the average of q_u . The regression line on q_u -depth relation has been usually used for the stability analysis of clayey ground. It has been known that the $q_{u(ave.)}$ is dependent on the quality of soil sample and that $s_{u(UCT)}$ may underestimate the true design strength, when the disturbance of samples is large²⁾. Considering the effect of sample quality, the method by unconfined compressive strength with the combined use of triaxial CU test (combined method) was introduced in the technical standard of port and harbour structures in 1990³⁾⁴⁾⁵⁾. However, according to the hearing from Ministry of Land, Infrastructure, Transport and Tourism, in most of the cases in practice after 1990, the design shear strengths of clay layer were determined by $s_{u(UCT)}$ in Eq.(1), and the cases where the combined method was used were rare. This seems to be because, although the cost of investigation becomes higher in the combined method, the benefit of the combined method has not been reported by the case studies.

In this study, the two cases where the combined method was used for determining the design shear

strength were shown and the effectiveness of the combined method was discussed.

2. COMBINED METHOD

The combined method in which both unconfined compressive strength and strength of triaxial CU test were used, was proposed considering the effects of sample disturbance, strength anisotropy of shear strength, rate effect on shear strength of clay⁴⁾⁵⁾. The triaxial test of this method is based on the idea of recompression method⁷⁾ to obtain the shear strength of clay after eliminating the effect of sample disturbance. Bjerrum proposed the "recompression" to obtain the true shear strength of clay by eliminating the effects of sample disturbance⁶⁾. Hanzawa used Bjerrum's method to determine the design shear strength for the stability analysis of quay wall constructed on soft marine clays⁷⁾. In Bjerrum's method, the triaxial compression and extension strengths must be carried out respectively after the K_0 consolidation of specimen with in-situ vertical and horizontal effective stresses in triaxial cell. Tsuchida et al²⁾ proposed to use the "simple CU test" instead of triaxial compression and extension test in Bjerrum's method, from the practical point of view. They proposed the method using both unconfined compression test and the simple CU test to determine the design shear strength considering the quality of samples.

2.1 Procedure of simple CU test

The procedure of simple CU test proposed by Tsuchida et al is as follows;

- 1) A specimen for triaxial test (the diameter is 35mm and the height is 80cm) is consolidated isotropically under the mean in-situ effective stress σ'_c for 120 minutes.
- 2) σ'_c is calculated as $(1+2K_0)/3\sigma'_{v0}$, where σ'_{v0} is the in-situ effective overburden stress. As the value of K_0 for Japanese marine clay, 0.5 is recommended.
- 3) After the completion of consolidation, the specimen is compressed with the strain rate of 0.1%/min.
- 4) The strength of simple CU test $s_{u(SCU)}$ is defined as the half of maximum deviator stress and is named as simple CU strength..

2.2 Procedure to determine design shear strength by unconfined compression strength and simple CU strength

From a soil sample taken by the fixed piston thin wall sampler, the diameter and the length of which are 75mm and 800mm respectively, three UCT and one simple CU test are carried out. By comparing the average value of $qu/2$ of three specimen, $s_{u(UCT)}$ to the simple CU strength $s_{u(SCU)}$, the quality of the sample and the design strength s_u^* are determined as follows (Fig.1):

Cluster I (Grade of quality 1, $s_{u(UCT)} > 0.80 s_{u(SCU)}$) :

Quality of sample is better than the average level. As the $s_{u(SCU)}$ may overestimate the design shear strength, s_u^* is determined as $0.75 s_{u(SCU)}$, where 0.75 is coefficient to correct the effects of strength anisotropy and the strain rate effects.

Cluster II (Grade of quality 2, $0.80 s_{u(SCU)} > s_{u(UCT)} > 0.70 s_{u(SCU)}$)

Quality of the sample is average level. As the design shear strength, both $s_{u(UCT)}$ and $0.75s_{u(SCU)}$ are available.

Cluster III (Grade of quality 3, $0.70 s_{u(SCU)} > s_{u(UCT)} > 0.60 s_{u(SCU)}$)

Disturbance is large. Design shear strength is $0.75 s_{u(SCU)}$.

Cluster IV (Grade of quality 4, $s_{u(UCT)} < 0.60 s_{u(SCU)}$)

The sample disturbance is very large. When the type of the sample disturbance is crack type, the design shear strength is $0.75s_{u(SCU)}$, while when the disturbance is remolding type, s_u^* is $0.65s_{u(SCU)}$. The type of disturbance is determine by the stress-strain curve of UCT as shown in Fig.2. The reason why the $0.65s_{u(SCU)}$ is recommended for the samples of remolding type disturbance is to avoid the overestimation of strength due to the reduction of water content in simple CU test.

3. DESIGN SHEAR STRENGTH IN THE 4TH RUNWAY PROJECT OF TOKYO INTERNATIONAL AIRPORT (HANEDA)

(a) Sample quality

(b) Determination of design shear strength

Fig.1 Estimation of sample quality and determination of design strength

Fig.2 Effect of disturbance on stress-strain curve

3.1 Overview of the geotechnical condition

The 4th runway project of Tokyo International Airport is to construct the 4th airport off-shore the existing airport as shown in Fig.3. The construction work started in 2005 and completed in 2010. In 2000,

the geotechnical investigation was carried out at the points shown in **Fig.3**. **Fig.4** is the cross section of soil layers at the construction site. As shown in **Fig.4**, the water depths at the site were from 13m to 20m. The soft alluvial clay layer (A_{c1} Layer) of 14-24m thickness overlaid the seabed. As the A_{c1} layer was almost normally consolidated, most part of the layer were improved by the sand drain method to accelerate the consolidation settlement and the increase of shear strength.

In the stability analysis of seawall for the runway, the estimation of second alluvial clay layer A_{c2} and the Pleistocene clay layers which underlain the A_{c2} layer with alternatively laid with sand layer. The Pleistocene clay layers were named as D_{c1} , D_{c2} and D_{c3} layers depending on the depth. The soil samples of Pleistocene layers were taken by fixed piston thin wall sampler or Denison type triple tube sampler. The largest depth of Pleistocene clay sample was 60m. The characteristics of A_{c2} layer and D_c layers were summarized as follows,

A_{c2} layer: silt containing fine sand, the liquid limit ranges from 30 to 60 % and the average is about 38%.

D_c layer: clayey silt, the liquid limit ranges from 35 to 70% and the average is about 40%.

3.2 Results of combined method to determine the design shear strength

Fig.5 shows the average of unconfined compressive strength $s_{u(UCT)}$ and the simple CU strength $s_{u(SCU)}$ with depth at the investigation sites shown in **Fig.3**. As shown in **Fig.5**, in the most sites, the values of $s_{u(SCU)}$ were larger than those of $s_{u(UCT)}$ and both were increasing with the depth. **Fig.6** shows the comparison

Fig.3 Points of geotechnical investigation in 4th runway project of Tokyo International Airport (Haneda)

Fig.4 Cross section of soil layers (4th runway project)

between $s_{u(UCT)}$ and $s_{u(SCU)}$. The data were classified with the depths of samples. As shown in **Fig.6**, the data were distributing in clusters I, II, III and IV and the quality

Fig.5 Unconfined compressive strength $s_{u(UCT)}$ and Simple CU strength $s_{u(SCU)}$ with depth

Fig.6 $S_u(UCT)$ and $S_u(SCU)$ (classified by sample depth)

Fig.7 $S_u(UCT)$ and $S_u(SCU)$ (classified liquid limit)

of sample was not dependent on the depth. Fig.7 shows the same data with the classification of the liquid limit of sample. In Fig.7, most data whose liquid limits are larger than 40% were plotted in the clusters I and II. However, the data whose liquid limit are less than 40% were plotted mainly in the clusters III and IV. Figs.6 and 7 shows that the quality of sample was determined not by the depth of sampling, but by the liquid limit of soil sample. The determination of design shear strength was carried out based on the simple CU strength and the correction factor 0.75⁸⁾.

4 DESIGN SHEAR STRENGTH OF INTER-MEDIATE SOIL IN SAKAI-MINATO PORT

4.1 Geotechnical investigation for construction of breakwater

The outer breakwater of Sakai-Minato Port in Tottori Prefecture was constructed in 1985. The new breakwater of 300m length was constructed in 2010, and the extended outer breakwater of 120m length was

constructed in 2012. Fig. 8 (a) and 8(b) show the liquid limit, plastic limit and natural water content with the depth at site A (the site of new breakwater) and site B (the site of extended outer breakwater), respectively.

As shown Figs 8, the ground of both sites consists of upper intermediate layer and the lower clayey layer. At the site B, there is a layer of sand containing silts.

Fig.9 is the grain size accumulation curve of samples taken at site A and B. The mean grain size of the upper intermediate soil was silt, and the intermediate soils were containing much sand. The lower clayey layer was constituted mainly by fine grained soils, showing the grain size accumulation curve of typical marine clay.

It is known that in the case of the intermediate soil, such as clayey soil containing much sand, the unconfined compressive strength usually under-estimates the true shear strength⁹⁾¹⁰⁾.

In the construction of new breakwater and the extended outer breakwater, the combined method is used to determine the design shear strength.

Fig.8(a) Liquid limit, plastic limit and water content (Sakai-Minato Port, Point A)

Fig.8(b) Liquid limit, plastic limit and water content (Sakai-Minato Port, Point B)

Fig10 shows the half of unconfined compressive strength $q_u/2$ and the 75% of simple CU strength, $0.75s_{u(SCU)}$, with depth at the sites A and B. As shown in the figure, the value of $q_u/2$ increases with the depth in both upper intermediate layer and the lower clayey layer, which was seen commonly in the typical marine clays. However, the values of 75% of simple CU strength, $0.75s_{u(SCU)}$ in the upper intermediate layer were more than 2 times $q_u/2$, and were almost same as $q_u/2$ for the lower clayey layer.

The stress-strain curves of unconfined compression test and the simple CU test of samples at the same depth were compared in **Fig. 11**. As shown in **Fig.11**, in the simple CU test of sample from the upper intermediate soils, the deviator stress continued to increase with compressive strain. However in the unconfined compression test, the deviator stress increased with the strain of 3-4% but the increase stopped after the axial strain more than 4%. In the samples from lower clayey layer, the stress-strain curve of unconfined compression test and the simple CU strength is were similar

Fig.12(a), (b) is the comparison of $s_{u(UCT)}$ with $s_{u(SCU)}$ in the form of **Fig.1**, and the evaluations of sample quality were made. The most of data from the upper

Fig.9 Grain size accumulation curves (Sakai-Minato Port)

intermediate soil were plotted in the cluster IV, which means that the sample disturbance is very large, it was evaluated that $s_{u(UCT)}$ underestimates the true design shear strength. The most of data from the lower clayey soil were plotted in the cluster I, which means that the sample disturbance is very small, and it was evaluated that $s_{u(UCT)}$ may overestimate the true design shear strength. In these cases, the design shear strength of upper intermediate soil was determined by using 75% of simple SU strength, $0.75s_{u(SCU)}$ ¹¹⁾. As the results,

Fig.10 Half of unconfined compressive strength $q_u/2$ and $0.75s_{u(SCU)}$ with depth (Site A and B, Sakai-Minato Port)

Fig.11 Stress-strain curves in simple CU test and unconfined compression test (Site B)

the new breakwater and the extended outer breakwater were constructed on the seabed without any ground improvement, although all the breakwaters in Sakai-Minato Port had been constructed after the improvements of foundation, previously. In the present cases, when $s_u(\text{UCT})$ was used as the design shear strength, the ground improvement would be necessary.

5 CONCLUSIONS

As the unconfined compressive strength (UCT) is influenced by the quality of sample, the strength determination method using both UCT and the strength obtained by triaxial CU test (simple CU test), which was named as “combined method”, had been proposed and was taken in the technical standard of port and harbor structure in 1990.

The combined method was used in 4th runway project of Tokyo International Airport and in the construction project of breakwater in Sakai-Minato Port. In the 4th runway project, it was found that the quality of high plastic clay taken by Denison sampler was fairly good and that the combined method was effective to avoid the underestimation of strength of low plastic clay.

In both cases, the data on clays of medium and high plasticity were classified as cluster I, meaning that the sample quality is high too much and that the use of UCT strength may overestimate the strength. On the other hand, the data of clay soils whose liquid limits were less than 40% and the data of intermediates soils containing sand were classified as cluster IV, which means that the sample quality is low and that the use of UCT strength will underestimate the strength.

In these two cases, the design shear strength was determined by the combined method. In the case of Sakai-Minato Port, the breakwater was constructed on the seabed without the improvement, extended outer breakwater were constructed on the seabed without any ground improvement, although the breakwaters in Sakai-Minato Port had been constructed after the improvements of foundation, previously. The combined method was effective to avoid the underestimation of strength of low plastic clay and intermediate soil.

REFERENCES

- 1) Nakase, A. (1967): The $\phi = 0$ analysis of stability and unconfined compression strength, *Soils and Foundations*, 7(2), 33-50.
- 2) Okumura, T. (1974): “Study on the disturbance of Clay and Improvement of Sampling Method”, *Technical Note of the Port and Harbour Research Institute*, No.193. (in Japanese)
- 3) Overseas Coastal Area Development Institute of Japan(2007) : Technical Standards and commentaries for Port and Harbour Facilities in Japan, Part 2, actions and material requirements, Chapter 3, Geotechnical conditions, 2 Ground constants, pp.210-234.
- 4) Tsuchida, T., Mizukami, J., Mori, Y. and Oikawa, K. (1989) :

Fig.12 $s_u(\text{UCT})$ and $s_u(\text{SCU})$ (Sakai-Minato Port)

New method for determining undrained strength of clayey ground by means of unconfined compression test and triaxial test, *Report of the Port and Harbour Research Institute*, 28(3), 81-145. (in Japanese)

- 5) Tsuchida, T. (2000): Evaluation of undrained shear strength of soft clay with consideration of sample quality, *Soils and Foundations*, 40(3), 29-42.
- 6) Bjerrum, L. (1973): “Problems of soil mechanics and construction on soft clays and structurally unstable soils”, State of the Art Report, *Proc., 8th ICSMFE*, Moscow, Vol.3, pp.111-159.
- 7) Hanzawa, H. and Kishida, T. (1982) : Determination of in-situ undrained strength of soft clay deposits, *Soils and Foundations*, 22(2), 1-14.
- 8) Watabe, Y., Tanaka, M., Noguchi, T., Miyata, M. (2008) : Geotechnical investigation at the planning site of the D-runway of the Tokyo International Airport, *Journal of J.S.C.E.*, C64(3), 585-597. (in Japanese)
- 9) Japan Geotechnical Society (1992): Intermediate soil -sand or clay?-, pp.55-84, 1992. (in Japanese)
- 10) Nakase, A., Katsuno, M., Kobayashi, M. (1972): Unconfined compression strength of soils of intermediate grading between sand and clay, *Report of Port and Harbour research Institute*, Vol.11, No.4, pp.83-102. (in Japanese)
- 11) Tsuchida, T. and Imamura, T. (2013): Evaluation of design shear strength of intermediate soil for construction of breakwater, *JGS Journal*, 8(1), 1-14. (in Japanese)